

# The Rôle of Strangeness in Astrophysics — an Odyssey through Strange Phases

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**Abstract.** The equation of state for compact stars is reviewed with special emphasis on the role of strange hadrons, strange dibaryons and strange quark matter. Implications for the properties of compact stars are presented. The importance of neutron star data to constrain the properties of hypothetical particles and the possible existence of exotic phases in dense matter is outlined. We also discuss the growing interplay between astrophysics and heavy-ion physics.

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## 1. Introduction

In the last few years, it became clear that strangeness has to be included as another degree of freedom in astrophysical systems. In this review, we will outline some recent developments in the study of matter with strangeness under extreme conditions with relevance to astrophysics. The field is growing rapidly, theoretically as well as experimentally, so we will not give an overview of the field but rather focus on some recent works about the properties of compact stars with a remark about the cosmological phase transition including strangeness.

The topics we are going to cover are: hyperons in neutron stars, kaon condensation in hadronic matter, H-dibaryon condensation, strange quark phase and twins, kaon condensation in quark matter, signals from proto-neutron stars with a strange phase, strange quark stars, new data from a isolated neutron star and the cosmological phase transition with strangeness.

The phase diagram of Quantum Chromodynamics (QCD) can be studied at large temperature and zero (or small) density by lattice calculations and by relativistic heavy-ion collisions. Neutron stars on the other hand probe QCD at high density and small temperature and provide therefore a complementary laboratory to study QCD under extreme conditions. Created by supernova explosions, neutron stars are compact remnants with masses around 1–2 solar masses and radii of about  $R \sim 10$  km. The central density of the compact star will be then several times normal nuclear matter

density  $n_0$ . More than 1000 pulsars, rotating neutron stars, are known today. The most precisely measured mass is the Hulse-Taylor pulsar with  $M = (1.4411 \pm 0.00035)M_\odot$ .

## 2. Strange hadrons in compact stars

The first systematic theoretical investigation of the composition of a neutron star was done in reference [1]. Nucleons as well as hyperons were included in the equation of state, nevertheless, in this early work they were treated as free particles. Hyperons were found to appear at  $4n_0$  ( $\Sigma^-$ ) and  $8n_0$  ( $\Lambda$ 's). The corresponding neutron star have too small a maximum mass of only  $M_{max} \sim 0.7M_\odot$  to agree with the observed pulsar masses. Therefore, strong interactions need to be incorporated for describing neutron stars! Investigations in different effective models in the last few years now essentially agree on a critical density of  $n_c \sim 2n_0$  (see [2]) for hyperons to appear in neutron star matter: effective nonrelativistic potential models [3], the Quark-Meson Coupling Model [4], extended Relativistic Mean-Field approaches [5, 6], Relativistic Hartree-Fock [7], Brueckner-Bethe-Goldstone [8], Brueckner-Hartree-Fock [9], Density-Dependent Hadron Field Theory [10] and chiral effective Lagrangians [11].

The abundance of hyperons in the interior raises the question about effects from hyperon-hyperon interactions which are (besides the known double hypernuclear events) essentially unknown. Hyperon-hyperon interactions can have drastic effects even on the global properties of neutron stars [12]: a phase transition to hyperonic matter is possible which generates a third family of solution of compact stars besides white dwarfs and neutron stars. Even self-bound compact stars can be generated for large attraction with rather small radii of about  $R \sim 7 - 8$  km. These hyperstars are also of relevance for relativistic heavy-ion collisions. Strange hadronic matter with a strongly attractive hyperon-hyperon interaction produces a second minimum at finite strangeness which is in accord with hypernuclear data. Matter in that second minimum is long-lived but not absolutely stable as there is an energy barrier only allowing multiple weak decays but not single weak decays [12].

Kaons can also appear in dense hadronic matter (for quark matter see the next section). As they have zero spin, they will form a Bose condensate in a neutron star (for a recent review see [13]). For a sufficiently reduced effective energy of the antikaons, neutrons will be transformed to protons and antikaons or equivalently electrons to  $K^-$  and neutrinos. The appearance of a kaon condensed phase depends crucially on the  $K^-$  optical potential at  $n_0$  which can be estimated from coupled channel calculations [14, 15] ( $-120$  MeV), selfconsistent calculations [16, 17, 18, 19] ( $-30$  to  $-80$  MeV) or  $K^-$  atomic data [20, 21] ( $-180$  MeV). A recent combined chiral analysis of the available data finds a rather shallow potential of only  $-55$  MeV [22]. The impacts for the mass-radius relation can be drastic if the optical potential for the  $K^-$  is larger than about  $-120$  MeV: compact stars with a kaon condensate can have radii of only  $R \sim 8$  km [23, 24] and produce again a third family of solution when taking into account the  $\bar{K}^0$  also [25]. A large region in the interior of the star may form geometric structures

in the mixed phase of nuclear matter and kaon condensed matter [23, 24, 26] which are determined by one model Lagrangian describing both phases simultaneously. The diameter of these structures is about 10–30 fm, and the spacing about 5–10 fm.

Other exotic particles can also appear inside a neutron star, like dibaryons or strangelets. Their appearance in dense matter marks the onset of the mixed phase to the deconfined quark matter. The H-dibaryon is a hypothetical six-quark state which is antisymmetric in flavor, colour and spin, hence it is also a boson with zero spin [27]. The stability of the H-dibaryon is closely connected with double  $\Lambda$  hypernuclear data as two  $\Lambda$ 's have the same quark content as the H-dibaryon and can be transformed into it via strong interactions. In addition to the three 'old' double hypernuclear events, two new events were reported this year: a  ${}_{\Lambda\Lambda}^4\text{H}$  by experiment E906 at BNL, and  ${}_{\Lambda\Lambda}^6\text{He}$  by experiment E373 at KEK (for references and a detailed interpretation of the presently available data see [28]). The double  $\Lambda$  hypernuclear data suggest an attractive force between the two  $\Lambda$ 's. No strong decay to the H-dibaryon has been observed which would give a lower limit to the mass of the H-dibaryon of  $m_H > 2m_\Lambda - B_{\Lambda\Lambda} \sim 2220\text{MeV}$ . Here  $B_{\Lambda\Lambda}$  is the binding energy of the two  $\Lambda$ 's. If the H-dibaryon appears in dense matter it will form a Bose condensate. The presence of the H-dibaryon will shift the maximum mass of a neutron star down but the corresponding radius up. This effect provides a constraint on the property of the H-dibaryon in dense matter as the maximum mass can not be lower than  $M = 1.44M_\odot$ . A deeply bound H-dibaryon with an attractive nuclear potential turns out to be not compatible with this constraint [29].

### 3. Strange quarks in compact stars

At sufficiently high density, the transition to deconfined strange quark matter should appear which is mostly modeled by the MIT bag model. It has been pointed out only in the last year, that this transition allows for the existence of a new class of compact stars: strange quark star twins [30, 31]. They are called twins, because there are two solutions to the Tolman-Oppenheimer-Volkov equations which have similar masses but different radii, one without and the other with a pure quark core. The compact stars with a quark core constitute a third family of solutions besides white dwarfs and neutron stars. The solution is stable and can in principle appear for (any) first order phase transition as pointed out already by Gerlach in 1968 [32]. The twin star solution within the MIT bag model gives radii which are only slightly smaller than for the neutron star solution,  $R = 10\text{--}12\text{ km}$ , and appear only for a narrow range of the bag constant,  $B^{1/4} = 178\text{--}182\text{ MeV}$  [31]. We point out, that such radii can be also reached without having a third solution. The unambiguous signal for twin stars would be the determination of the mass and radii of neutron stars which have similar masses but different radii.

The detailed properties of the quark phase in compact stars has been a topic of recent interest (for a review see [33]). Here, we just report on one of the most recent developments in this rapidly evolving field of color superconductivity concerning strangeness. For three-flavour QCD with massless quarks, a colour-flavour locked (CFL)

phase will form. For a finite strange quark mass, the CFL phase will be under stress. Low lying excitations appear which have the quantum numbers of the pseudoscalar meson octet, i.e. of pions and kaons. These pionic and kaonic excitations can form a pion or kaon condensate in the quark phase of the compact star [34]. It is interesting to note that kaon condensation in quark matter actually reduces the number of strange quarks contrary to kaon condensation in hadronic matter. The kaon condensed phase in quark matter will not change the global properties of the compact star as the effects on the equation of state are likely to be negligible. But the transport properties of quark matter will be affected strongly.

#### **4. Signals for a strange phase in compact stars**

There are at least two signals for the presence of strange hadrons and/or strange quarks in the interior of neutron stars which are common for all strange phases regardless of the details of the composition. We discussed one common signal so far, namely that a third family of compact stars can appear with smaller radii than ordinary neutron stars which has been shown to be the case for hyperon matter [12], for kaon condensation [25] and for strange quark matter [30].

Another signal has been proposed recently which again is possible for the all three kinds of strange phases: the neutrino flux from a proto-neutron star in a supernova [35]. A newly born hot neutron star with a strange phase can support more mass than a cold one so that the cooled neutron star has to collapse to a black hole. The flux of neutrinos emitted from the supernova event will stop suddenly when the black hole is formed. The delayed collapse happens again for every strange phase discussed so far, be it with hyperons, kaons or strange quarks. The timescale to the instability lies typically below a minute and is slightly different depending on the critical density at which strange particles appear. The mass range of the instability is rather similar,  $M = (1.6\text{--}2.2)M_{\odot}$ , so low mass black holes will be produced in either scenario.

#### **5. New approaches to dense QCD**

The 'standard' model for dense QCD was to use the MIT bag model with free quarks, whose results depend strongly on the unknown bag parameter. Only recently did one start to explore other approaches to dense QCD, all but the first includes effects from the strange quarks: Schwinger-Dyson model [36], massive quasiparticles [37, 38], Nambu–Jona-Lasinio model [39] and perturbative QCD [40, 41]. We will focus on the latter one in the following in more detail. We note that we discuss in this section the global properties of bulk quark matter, while section 3 about color superconductivity deals with two quark interactions. Both pictures are then to be seen complementary.

The underlying new physical picture for cold and dense QCD is that the phase transition is from hadrons/massive quarks to massless quarks, i.e. one has to study the chiral phase transition not the deconfinement transition. The transition from hadrons

to massive quarks is smooth as there exists no order parameter at zero temperature and finite density contrary to the chiral phase transition. We take the thermodynamic potential up to second order in the strong coupling constant  $\alpha_s$  as a model for dense QCD and compute thermodynamically consistent the pressure, number density and energy density. The coupling constant  $\alpha_s$  is running and depends on the renormalization subtraction point  $\bar{\Lambda}$ .

The behaviour of the perturbative series looks reasonable, but the results depend so strongly on  $\bar{\Lambda}$  that it is constrained by physics with a reasonable range of  $\bar{\Lambda}/\mu = 2-3$  (case 2 and 3 in the following) where  $\mu$  is the quarkchemical potential. Note that different values of  $\bar{\Lambda}$  correspond to different scales, i.e. different chemical potentials. As the density grows like  $\mu^3$  a slightly smaller scale results in a tremendous increase in the density. In every case, the pressure turns out to be far from a free gas even for large values of the quark chemical potential. There is a 30% reduction in the pressure compared to a free gas at  $\mu = 1$  GeV, and still a 7% reduction at  $\mu = 100$  GeV! So quark matter can definitely not be described by a free gas, especially not for densities of interest for compact stars. For all cases does the pressure vanish at some  $\mu_c$  (here for certain does perturbative QCD break down). The maximum mass for a pure quark star, ignoring for a moment a hadronic mantle, is  $M = 1.05M_\odot$  for case 2 and  $M = 2.14M_\odot$  for case 3 with radii of  $R = 5.8$  km and  $R = 12$  km, respectively [40]. Similarly small values for the mass and radius of quark stars were also found in [38].

The matching to a low density equation of state can be classified to be either weak or strong. For a weakly first order phase transition or a crossover, the pressure rises strongly before it reaches the pressure curve for the massless quarks. For a strong first order transition, the pressure has to rise slowly. Interestingly, asymmetric matter up to say  $2n_0$  can be parameterized by  $E/A \sim 15$  MeV  $n/n_0$  (see [42]), so that the baryonic pressure is just 4% that for a free quark gas at  $n_0$ ,  $p_B \sim 0.04(n/n_0)^2 p_{\text{free}}$ ! This slow rise of the pressure at least allows for a strong first order transition. Adding a hadronic equation of state to the quark equation of state, gives ordinary neutron stars with a quark core (hybrid stars) for both cases. In addition, a strong phase transition enables again a third class of compact stars, this time with masses of only  $M \sim 1M_\odot$  and radii of only  $R \sim 6$  km! The quark phase dominates the composition of the compact star, as the maximum density in the quark core is  $15n_0$  and the hadronic pressure is small compared to the quark pressure [41].

The mass-radius relation of neutron stars can therefore tell us something about the order of the phase transition in dense QCD. The analysis of the data from isolated neutron stars will be able to pin down the mass and the radius simultaneously. The radio-quiet neutron star RX J185635-3754 is the closest one known to our planet [43]. The spectra is nearly thermal with an effective temperature of  $T \sim 49$  eV. First parallax measurements by the Hubble Space Telescope with a distance of about 60 parsec give a black-body radius of only  $R_\infty = 6$  km [43]. A more detailed analysis of the combined data from ROSAT, EUVE and HST, including effects from the atmosphere, finds a best-fit mass and radius of  $M \sim 0.9M_\odot$  and  $R \sim 6$  km [44]! The authors conclude that

these values together are not permitted by any plausible equation of state, even not that for absolutely stable strange stars. We note, however, how close they are to the above values for quark stars within perturbative QCD. Nevertheless, the parallax measurement in [43] is questioned in [45] and a radius of  $R_\infty = 15 \pm 6$  km is found. The release of the newest data from HST next year will settle this discrepancy. Gravitational micro-lensing is another promising tool to find small compact stars. The MACHO project reports events with a mass of  $M \sim 0.5M_\odot$  from several years of observation towards the Large Magellanic Cloud [46]. Events with  $M = 0.13M_\odot$  and  $M = 0.25M_{\text{Jupiter}}$  are detected at the globular cluster M22 [47].

## 6. Strange cosmological phase transition

Strangeness is also of interest for the early universe, as strange stars might have been produced there. The newly formed strange star faces several obstacles to survive (see [48] for an overview): the mass number must be smaller than  $A < 10^{49}$  due to the horizon at a time of  $t \sim 1\mu s$  after the big bang,  $A > 10^{23}$  so that the neutron capture rate is not in conflict with the big bang nucleosynthesis and  $A > 10^{30-40}$  so that the strange star does not evaporate completely at a temperature of  $T \sim 160$  MeV. A typical compact star on the other hand has  $A \sim 10^{57}$ . A possible solution is to propose that an inflation happens at the quark-hadron phase transition [49]. The exponential expansion and supercooling allows the production of large quark stars with masses of  $M \sim (10^{-2} - 10)M_\odot$ . This scenario is interesting as it is able to produce small compact stars below  $1M_\odot$ . Standard supernova simulations usually get neutron stars above that mass. The crucial point for quark inflation to happen is to assume a large surface tension of  $\sigma = 50 - 120$  MeV fm<sup>-2</sup>. Therefore, hadron bubbles have to expand tremendously to overcome the surface energy which causes the inflation. Note that such a large surface tension would make the mixed phase region from hadrons to quarks in compact stars disappear!

## 7. Astrophysics versus Heavy-Ion Physics

There are strong relations between the field of astrophysics and heavy-ion physics. Following the topics discussed here, we list some of them.

Hyperstars, compact stars composed of strongly attractive hyperonic matter, are connected to strange hadronic matter and MEMOs (see [50] and references therein). If hyperstars exist, strange hadronic matter has to exist and can possibly be formed in relativistic heavy-ion collisions.

Kaons in the medium can be studied as well as for kaon condensation in neutron stars as well as for the subthreshold production of antikaons in heavy-ion collisions. If kaon condensation is so strong as to change the global properties of compact stars, it certainly will impact the production of antikaons in dense matter. Nevertheless, the optical potential probed in heavy-ion collisions will be in general different from that in neutron stars so that a direct comparison has to be taken with care (see [18])!

Properties of the H-dibaryon in the medium as well as other exotic stable particles, which dedicated heavy-ion experiments are hunting for, can be constrained by astrophysical (pulsar) data. Dibaryons with strangeness can be formed in relativistic heavy-ion collisions and it is possible to detect them by their decay properties [51].

The existence of strange stars is ultimately connected with the stability of strangelets and hence, their searches in relativistic heavy-ion collisions, too (see [52] and references therein). If strange stars exist, strangelets accessible to heavy-ion experiments are likely to be stable but they are short-lived when taking into account shell effects (for an overview see [53]).

Quark matter at finite density behaves highly nonideal around the chiral phase transition similar to matter at finite temperature around  $T \sim T_c$  (see e.g. [54]) which is probed in relativistic heavy-ion collisions.

Finally, the cosmological phase transition might allow for an inflation. If this is the case, then it will have strong impacts on the study of the deconfinement phase transition in ultrarelativistic heavy-ion collisions and can result in an explosion. The recently measured exotic two-particle correlation at the Relativistic Heavy-Ion Collider might be an indicative for such a scenario [55].

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